

# Development of AlGaN/GaN HEMT Technology for Highest Frequency Operation

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## Abstract:

The ever increasing demand for high power, high frequency, and high temperature devices has prompted much research into AlGaN/GaN high electron mobility transistors (HEMTs) because of their high breakdown voltage and excellent electron transit properties. Optimized AlGaN/GaN HEMTs promise to play a pivotal role in next generation mobile phone base stations, radar, mixers, oscillators, and attenuators in both commercial and military applications. This work characterizes the performance of AlGaN/GaN HEMTs on SiC in relation to source-gate spacing. Development of HEMT technology is explored utilizing T-gates and optimized ohmic contacts for improving the high frequency operation of future HEMT generations.

## Introduction:

Gallium nitride (GaN) HEMTs excel over competing technology for high power, high frequency applications. GaN HEMTs have an order of magnitude higher power density and higher efficiency over silicon (Si) and gallium arsenide (GaAs) transistors, allowing a ten time size reduction for the same output power, while simultaneously saving material cost. The wide band gap (3.4 eV) allows for rugged high-voltage, high-temperature application extensively covering both commercial and military markets [1].

AlGaN/GaN HEMTs with varying source-gate spacing were fabricated using a standard technology process developed in our lab. HEMTs were characterized by their DC, I-V, C-V characteristics, Hall measurements, and high frequency (HF) measurements. A hydrogen silsesquioxane (HSQ)/polymethyl methacrylate (PMMA) T-Gate process was then developed to increase the  $f_t$  and  $f_{max}$  of the next generation HEMTs. Ohmic contacts with improved morphology and line edge definition after annealing were also investigated.

## Experimental Procedure:

Transistors were fabricated on a semi-insulating silicon carbide (SiC) substrate (Figure 1) with a layer stack grown by metal-organic-vapor-phase-epitaxy (MOVPE). Transistor fabrication began with mesa isolation performed by argon sputtering followed by ohmic contact and Schottky gate metallization. Ohmic contacts consisted of Ti/Al/Ni/Au metallization from bottom to top with a respective layer thickness of 35/200/40/100 nm. Schottky gate metallization was Ni/Au with thickness 25/100 nm with 170 nm gate length. Contact pads to the source, gate, and drain consisted of Cr/Au

Source	Gate	Drain
GaN		3 nm
AlGaN		20 nm
GaN		3 $\mu\text{m}$
SiC		380 $\mu\text{m}$

Figure 1: AlGaN/GaN HEMT layers.

with respective thickness 20/400 nm. Contact resistance was  $0.68 \Omega \cdot \text{mm}$  and the sheet resistance was  $422 \Omega$  per square, determined by transmission line measurements.

T-Gate processes can be categorized in one-step and in two step-processes. In the latter, the gate foot is defined separately from the gate head. This approach was chosen for investigation utilizing HSQ and PMMA as e-beam resists. HSQ was used for the gate foot because of its availability and high resolution, while a PMMA tri-layer (200K/200K/950K) was chosen for the gate head.

E-beam markers maintaining a better morphology and line edge definition were investigated to automate T-gate alignment without any undesired offsets from source or drain. In this manner, the introduction of an additional marker layer could be circumvented. Ti/Al/Mo/Au metallurgy was tested as an alternative to the standard contact metallurgy of Ti/Al/Ni/Au.

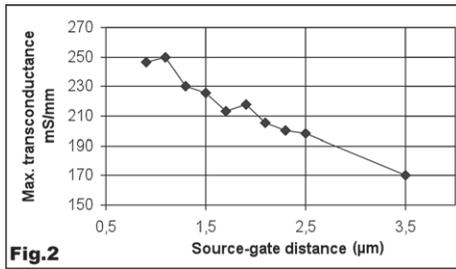


Figure 2: Maximum transconductance.

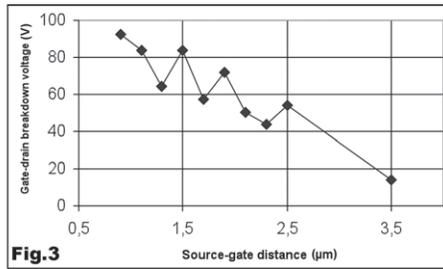


Figure 3:  $V_{gd, breakdown}$

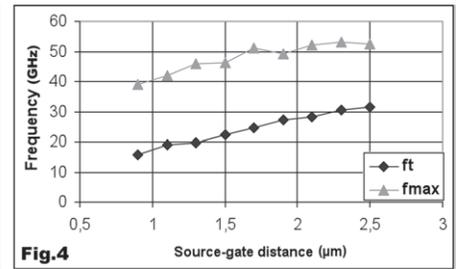


Figure 4: Maximum transit frequency ( $f_t$ ) and maximum frequency of oscillation ( $f_{max}$ ).

## Results:

In the transistor experiment, source resistance  $R_s$ , was decreased by aligning the gate closer to the source during the gate fabrication process step. As intended, the external transconductance  $g_{m,ext}$  increased with a decreasing source resistance (Figure 2).

Moving the gate from the drain towards the source increases gate-drain distance simultaneously. For a HEMT, the largest potential difference can be found between the gate and the drain if a common bias point is considered. In this way an increased source-gate distance lowers the gate-drain breakdown voltage  $V_{gd, breakdown}$  (Figure 3).

Both results, extracted from DC measurement data, showed an improvement of the device regarding  $g_{m,ext}$  and the  $V_{gd, breakdown}$ . Cut-off frequency,  $f_t$ , increases inversely with gate-source capacitance,  $C_{gs}$ , and proportionally with  $g_{m,ext}$ . However, high frequency measurements do not exhibit an increase in  $f_t$  despite the lowered source resistance and higher  $g_{m,ext}$  (Figure 4). The reason for the decrease of both operating frequencies with a lowered source-gate distance is believed to result from more  $C_{gs}$  than  $g_{m,ext}$  increase.

A reproducible two-step e-beam T-Gate process was successfully developed (Figure 5) with HSQ/PMMA. An excellent gate foot width of 90 nm was achieved with experiments yielding good results down to 40nm. Future work will consist of gate recess etching in order to keep a reasonable aspect ratio of the HEMT gate structure.

/Al/Mo/Au based ohmic contacts yielded better morphology and line edge definition after annealing than our previously optimized Ti/Al/Ni/Au contacts. In comparison to optimized contacts, Ti/Al/Mo/Au contacts had double the contact resistance ( $R_c = 1.2 \Omega/mm$ ) and resulted in an order of magnitude higher contact resistivity of about  $\rho_c = 3.82 \cdot 10^{-5} \Omega \cdot cm^2$ , indicating that more investigation of layer properties would be needed to lower resistance.

## Conclusion:

Analysis of standard technology fabricated transistors with varying source-gate distances was performed to establish a starting point of further investigations. A HSQ/PMMA T-Gate process was successfully developed for next generation AlGaIn/GaN HEMTs. Currently, the T-Gate process step is being integrated into the standard HEMT process with a gate recess etch, and gate dimension optimization to reduce  $C_{gs}$  and improve  $f_t$  will follow soon thereafter. To allow automated e-beam T-Gate alignment, Ti/Al/Mo/Au e-beam markers with lower resistivity will also be further investigated.

## Acknowledgements:

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## References:

- [1] Mishra et al, "AlGaIn/GaN HEMTs-An Overview of Device Operation and Applications," Proceedings of the IEEE, vol. 90, pp.1022-1031, June 2002.

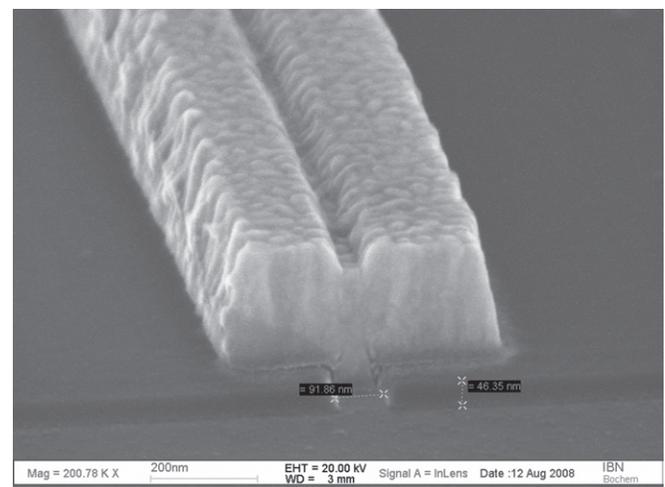


Figure 5: T-Gate with 90 nm gate foot width, 46 nm gate foot height, 250 nm gate head height, and 490 nm gate head width.